ONE DIMENSIONAL MAGNETOHYDRODYNAMIC SIMULATIONS OF EXPLODING FOIL OPENING SWITCHES

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Abstract

Exploding foil opening switches are employed at the Air Force Weapons Laboratory on a large, low inductance, capacitor bank in an inductive store configuration to drive fast z-pinch cylindrical liner implosions. An experimental program to evaluate the performance of these opening switches is complemented by a theoretical effort to investigate methods of improving their performance. The magnetohydrodynamic (MHD) plasma simulation code, MAGPIE, has been used to evaluate several different configurations and techniques for improving the performance of these switches. Numerical results are presented for the following configurations : (1) foil in one atmosphere of inert gas, (2) foil in thin polyethylene sandwich, (3) foil in semi-infinite polyethylene sandwich, and (4) foil with high explosive compression in a polyethylene sandwich. Comparisons with experimental results are also presented.

Introduction

Electrically exploded aluminum foil fuses have been used as current interrupters in high energy inductive store systems for several years at the Air Force Weapons Laboratory (AFWL) to power plasma physics experiments in the AFWL Shiva X-Ray Source Technology Development Program. These opening switches have effectively interrupted up to 20 mega-amperes of current while withstanding imposed electric fields of 1-10 kv/cm in transferring energy from inductive stores to loads of mixed inductive and ohmic impedances used in a variety of experiments.[1] An ongoing experimental program to characterize the performance of exploding foil fuses has investigated various geometries, fuse materials, quench media, and energy regimes.[2,3,4,5] A companion theoretical effort has used the results of the experimental fuse program to conduct pulse power circuit optimization calculations along with one and two dimensional magnetohydrodynamic (MHD) simulations of imploding plasma liner loads driven by a fused inductive store circuit.[6] This present study is the result of an effort to apply one-dimensional MHD numerical simulation techniques to the exploding foil fuse concept in an attempt to better understand the physical processes involved and to investigate ideas for improving fuse performance.

Effective energy transfer from a primary capacitive energy storage system to a typical plasma physics experiment through an inductive store circuit requires that the opening switch meet several requirements. To efficiently charge the intermediate inductive store, the switch must conduct a large current for some time with a small initial resistance and minimal increase in resistance prior to onset of vaporization. To optimally transfer energy from the inductive store to a load, the switch must attain the highest possible resistance in the vapor phase. Finally, the exploded fuse must be capable of holding off electric fields up to about 20 kv/cm for the length of the experiment without suffering a restrike.

The MHD plasma simulation code, MAGPIE/CHROME, was used to evaluate the relative performance of different fuse configurations and to investigate techniques for improving fuse performance. MAGPIE/CHROME is a full MHD treatment, one-dimensional, cylindrical geometry, Lagrangian plasma simulation code developed at Lawrence Livermore National Laboratory and the AFWL.

Fuse Model/Experimental Results

A typical fuse consists of a thin (2.54×10^{-5} to 7.62×10^{-5} m) foil of aluminum or copper embedded in a porous, high melting point temperature, dielectric quench medium. Commercially available soda-lime spherical glass beads of 10^{-4} m diameter have been routinely used as a quench material for a number of years with good success. A recent experimental fuse series conducted at the AFWL investigated a number of different quench materials and bead sizes.[7] Quartz grains of 10^{-5} m average size seem to offer a moderate, but not dramatic, increase in final fuse vapor resistivity. The metallic vapor hydrodynamically expands into the empty spaces between the grains of the quench medium and cools by condensation before reaching a temperature where significant ionization can occur.

In order to compare fuse performance among many different experiments and configurations, the resistance measurement is scaled by the length-area ratio of the original metallic fuse conductor to obtain a normalized effective resistivity. This effective resistivity is then plotted against the electrical energy deposited in the fuse, scaled by the mass of the fuse. What results then from a given set of experiments is a canonical representation of typical fuse behavior as is shown in figure 1. Here the effective resistivity of an aluminum fuse in ohm m is plotted against the specific electric energy, in j/gm, deposited in the fuse through joule heating. With such a curve in hand, one can then answer questions about the resistance behavior profile of a similar fuse, in an equivalent circuit, on a corresponding time scale, but with a different cross-sectional area, length and total mass.

Some qualitative features of this experimentally determined curve are worth mentioning. The melting of the aluminum in the 10^{3} to 3.0×10^{3} j/gm energy range is evident along with the greater rate of increase in effective resistivity in the explosive vaporization phase in the 7.0×10^{3} to 10^{4} j/gm range. The vast majority of aluminum fuse physics experiments show a leveling off, or plateauing, of the effective resistivity between 5×10^{-6} and 10^{-5} ohm m in the vapor phase above about 10^{4} j/gm deposited specific energy.

Code Capability/Simulation Configurations

MAGPIE/CHROME is a one dimensional Lagrangian code for treating magnetohydrodynamic (MHD) problems in cylindrical coordinates. The code is capable of dealing with elemental metals, such as aluminum and copper, from the cold solid density state to the gaseous vapor and plasma state. Solid insulators, such as polyethylene, in addition to monoatomic neutral gases, are also modelled in the code. The equation of state treatment for the solid, liquid and cool vapor phases is relatively primitive, but contains enough

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1985**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **One Dimensional Magnetohydrodynamic Simulations Of Exploding Foil Opening Switches**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Weapons Laboratory Plasma Physics branch AFWL/AWPP Kirtland AFB, NM 87117-6008**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT	b ABSTRACT	c THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

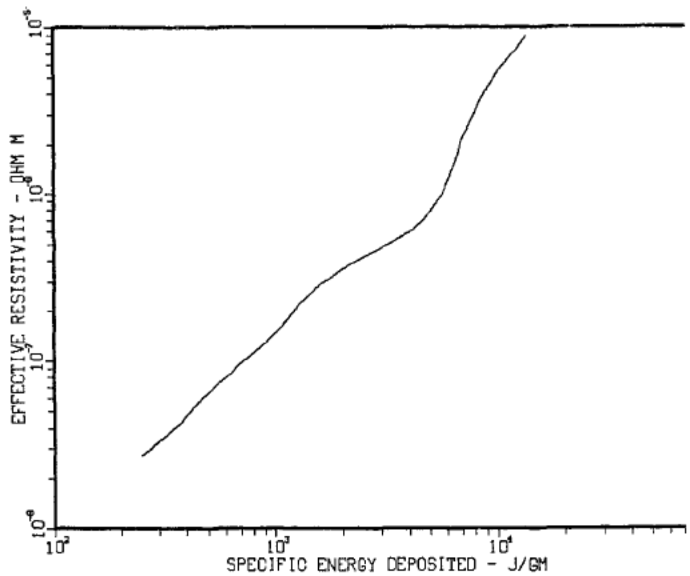


Figure 1. Experimental result for exploding aluminum foil fuse. Effective resistivity versus specific electrical energy deposited.

relavent physics to make the results a reasonable approximation to reality. The CHROME portion of the code treats the monoatomic vapor state above about 0.5 ev. The CHROME physics options selected for this particular study included a simple Saha equilibrium ionization model.

Four different aluminum fuse/insulating tamper configurations were run for this study. The detailed treatment of the hydrodynamic expansion of an aluminum vapor into a matrix of glass beads is a multi-dimensional problem far beyond the scope of this paper. The inertial tamping effect of the quench media on the rapidly expanding metallic vapor may be approximated by choosing a suitable mass of insulating material to abut the metallic fuse material. The actual physical process of glass beads quenching the hot aluminum vapor before significant ionization can occur is rather difficult to model in a one-dimensional formulation.

The current source for all cases was the 6.5 mj SHIVA Star fast capacitor bank.[8] The fuse was modelled in MAGPIE as being directly driven through a single RLC circuit loop with the following parameters.

$$C = 1313.0\mathrm{X}10^{-6} \text{ farads}$$
$$V = 10^{5} \text{ volts}$$
$$L = 10^{-8} \text{ henrys}$$

These circuit parameters result in a $5.7\mathrm{X}10^{-6}$ s quarter cycle time and a short circuit peak current of $3.6\mathrm{X}10^{7}$ amps. The fuses all had the same cross-sectional area, length, and mass, $1.36\mathrm{X}10^{-4}$ m^2, 0.5 m, and 183.1 gm respectively. The fuses were modelled as right circular cylindrical shells with current flow in the axial direction. The change in inductance due to movement and expansion of the fuse material was assumed to be small compared to the total circuit inductance and was neglected in the calculations.

Case 1 :
$2.54\mathrm{X}10^{-5}$ m thick aluminum foil in one atmosphere argon

Case 2 :
$2.54\mathrm{X}10^{-5}$ m thick aluminum foil between two $1.27\mathrm{X}10^{-4}$ m thick polyethylene annular cyclindrical shells surrounded by one atmosphere argon

Case 3 :
$2.54\mathrm{X}10^{-5}$ m thick aluminum foil between two 0.10 m thick polyethylene annular cylindrical shells surrounded by vacuum

Case 4 :
$5.08\mathrm{X}10^{-5}$ m thick aluminum foil with a 10^{-3} m thick annular cylindrical shell of Comp B/Grade A high explosive in contact with outer surface of aluminum and the aluminum/high explosive sandwich between two 0.05 m thick polyethylene annular cylindrical shells surrounded by vacuum. The outer surface of the high explosive was detonated $160.0\mathrm{X}10^{-9}$ s before the outer surface of the aluminum reached the vaporization phase. This time period was determined to be the time required for the high explosive detonation wave to propagate completely through the high explosive shell. This criteria was chosen to apply maximum pressure from the high explosive burn at time of fuse vaporization.

One of the major goals of this study was to investigate the effect of different tamping configurations on fuse effective resistivity performance. Also of interest is the comparable maximum effective resisitivities from each of the calculations with each other and with experimental results. The maximum and final temperatures of the metallic vapor along with the amount of hydrodynamic expansion experienced in the different cases is also of interest. It is hoped that these results might generate conceptual ideas for improving our understanding of how exploding foil fuses work. Finally, designs for further fuse experiments may be realized from this study.

Simulation Results

The results of the four simulations are presented in plots and a table. The plots are of fuse effective resistivity versus specific electrical energy deposited and the effect of the hydrodynamic expansion of the metallic fuse conductor/insulating tamper package. Table I shows a summary of the results of each of the simulations. The differences will show up in the following areas : (1) time history of current behavior after interruption, (2) peak fuse effective resistivity, (3) time history of effective resistivity after interruption, and (4) dynamical interaction of the expanding aluminum vapor with the tamping medium. Side effects of the different configurations will also be observed in the densities and temperatures present in the aluminum vapor as a function of time.

Case 1. One Mil Aluminum Foil in One Atmosphere Argon

The case of the foil in one atmosphere of a gas represents a situation where the tamping mass is the amount of gas that experiences the shock wave from the exploding aluminum foil. Case 1 results are shown in figure 2.

Case 2. One Mil Aluminum Foil in Thin Polyethylene Sandwich

This case probably represents the closest facsimilie to the mass tamping configuration experienced in the actual fuse experiment with a glass bead quench. No attempt was made to actually implement an equation-of-state for glass beads, but instead to simulate the approximate inertial mass tamping effect of the glass bead quench with a solid insulating material. The results from case 2 are shown in figure 3.

Case 3. One Mil Aluminum Foil in Thick Polyethylene Sandwich

The somewhat better performance of the aluminum

TABLE I

	Case 1	Case 2	Case 3	Case 4
Avg initial di/dt (amps/s)	-2.7×10^{14}	-2.65×10^{13}	-9.5×10^{13}	-1.2×10^{14}
Max resistivity (ohm m)	3.0×10^{-5}	1.0×10^{-5}	2.5×10^{-5}	3.45×10^{-5}
Energy at max resistivity (kj/gm)	5.5	8.0	9.5	8.7
Resistivity at 10 kj/gm (ohm m)	1.0×10^{-7}	2.5×10^{-6}	1.8×10^{-5}	3.1×10^{-5}
Avg expansion velocity (m/s)	0.86×10^{4}	3.2×10^{3}	1.6×10^{3}	1.2×10^{2}
Peak fuse temperature (ev)	3-4	3-4	3-4	1-1.5
Thermal restrike	yes	no	no	no

fuse/thin polyethylene sandwich led naturally to try a fuse in a thick polyethylene sandwich, i.e., essentially a semi-infinite mass of tamping material. The choice of 0.10 m thick polyethylene cylinders was somewhat arbitrary; the only criteria being that they must be much more massive than the aluminum and be many times thicker than the sound speed times several microseconds. Case 3 results are presented in figure 4.

Case 4. Two Mil Aluminum Foil/High Explosive Compressor

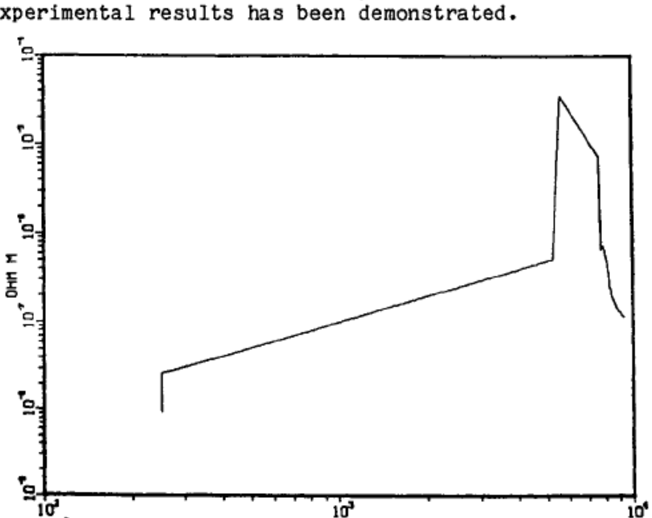
The last case considered the most massive tamping configuration possible : driving a compression wave generated by a high explosive into the aluminum at the time that vaporization is just beginning. The cylindrical aluminum fuse foil was made twice as thick as in the previous three cases and brought into a 0.42 m radius in order to get the same cross-sectional area as the foils employed in cases 1-3. A 10^{-3} m thick Comp B/Grade A high explosive cylindrical shell was place against the outer surface of the aluminum foil. The foil/high explosive combination was placed between two 0.05 m thick polyethylene annular cylindrical shells. The results from the high explosive compressed fuse simulation are shown in figure 5.

Conclusion

One-dimensional magnetohydrodynamic simulations of cylindrical exploding foil aluminum fuses have demonstrated the effect of varying the mass of tamping media that the metallic vapor interacts with during its explosive expansion phase. Rough qualitative agreement of fuse effective resistivity performance with experimental results has been demonstrated.

References

1. Reinovsky, R. E. et al, "Inductive Store Pulse Compression for Driving High Speed Plasma Implosions", IEEE Transactions on Plasma Science, PS-10(2), June 1982.
2. Stuerke, C. et al, "Multi-Megamp, Multi-Terawatt Inductive Pulse Compression System Operation", Digest of Technical Papers, 3rd IEEE International Pulsed Power Conference, Albuquerque, NM, (1981).
3. Henderson, R. P. et al, " Preliminary Inductive Energy Transfer Experiments", Digest of Technical Papers, 2nd IEEE International Pulsed Power Conference, Lubbock, Texas (1979).
4. Reinovsky, R. E. and Smith, D. L., "Fuse Switches for High Current Inductive Pulse Compression Systems", Final Report on Proceedings Workshop on Repetitive Opening Switches, Durango, Colorado, (January 1981).
5. Bueck, J. C. and Reinovsky, R. E., "The Effects of Cryogenic Initial Temperatures on Aluminum and Copper Electrically Exploded Foil Fuses", Digest of Technical Papers, 4th IEEE International Pulsed Power Conference, Albuquerque, NM, (June 1983).
6. Roderick, N. F. et al, "Theoretical Modelling of Electromagnetically Imploded Plasma Liners", Journal of Lasers and Particle Beams (1983), vol. 1, part 2, pp181-206.
7. Bueck, J. C. private communication, to be published
8. Reinovsky, R. E. et al, "SHIVA STAR Inductive Pulse Compression System", Digest of Technical Papers, 4th IEEE International Pulsed Power Conference, Albuquerque, NM, (June 1983).



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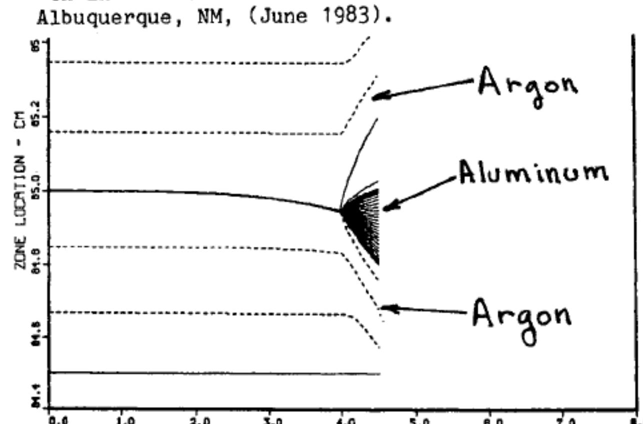

b)

Figure 2. Case 1. One mil foil in one atmosphere argon. a) Effective resistivity versus specific electrical energy deposited. b) Zonal locations versus time.

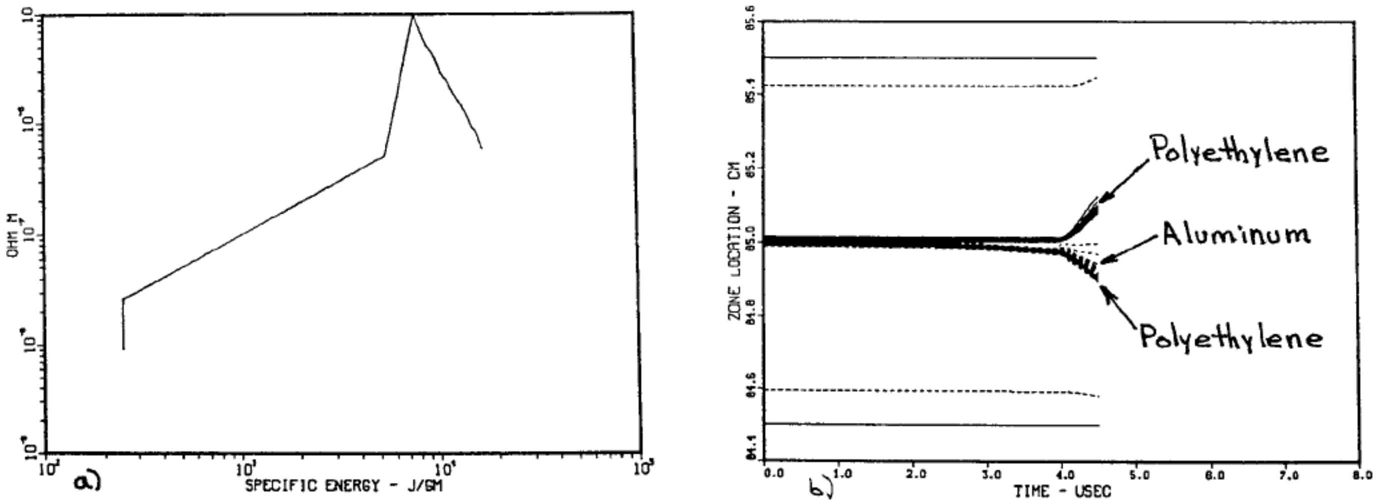

Figure 3. Case 2. One mil foil in thin polyethylene sandwich. a) Effective resistivity versus specific electrical energy deposited. b) Zonal locations versus time.

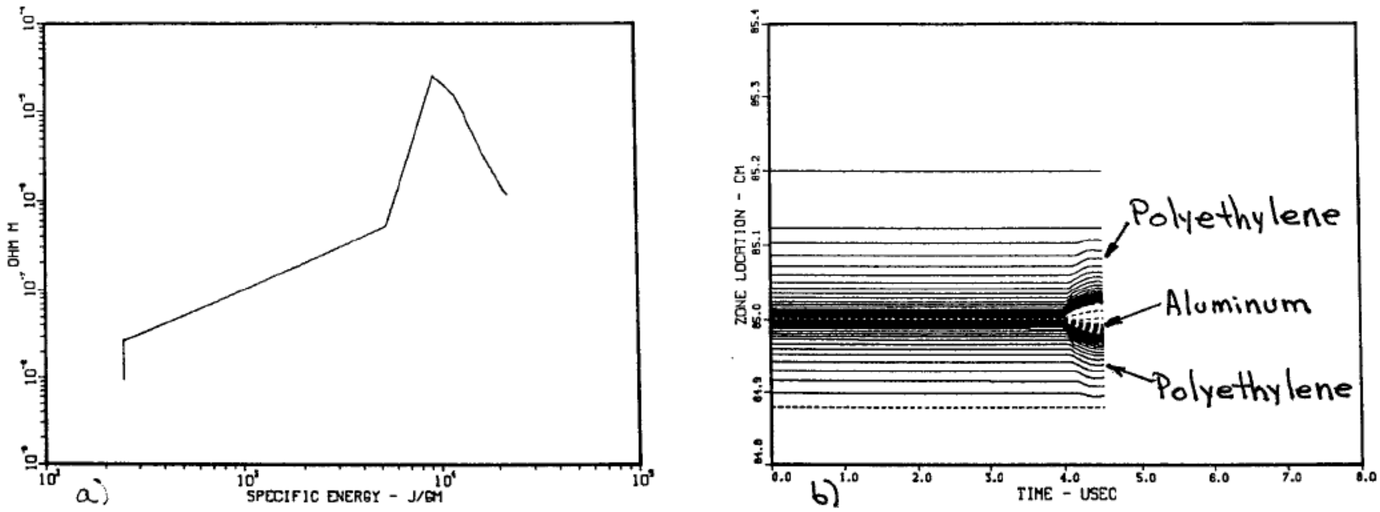

Figure 4. Case 3. One mil foil in thick polyethylene sandwich. a) Effective resistivity versus specific electrical energy deposited. b) Zonal locations versus time.

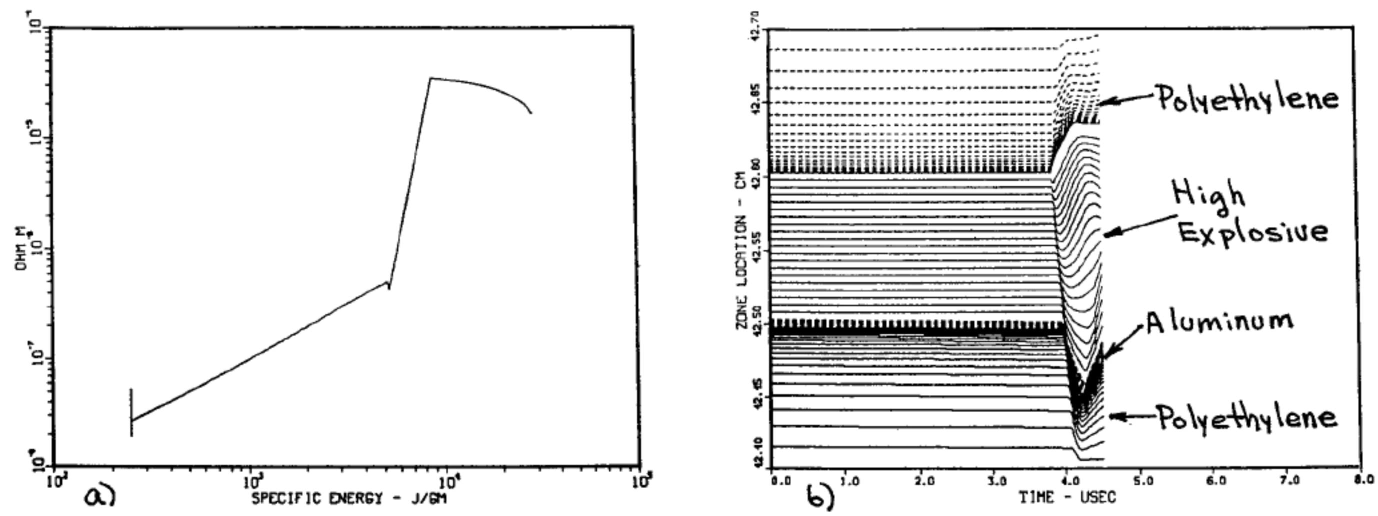

Figure 5. Case 4. Two mil foil in with high explosive compressor in thick polyethylene sandwich. a) Effective resistivity versus specific electrical energy deposited. b) Zonal locations versus time.